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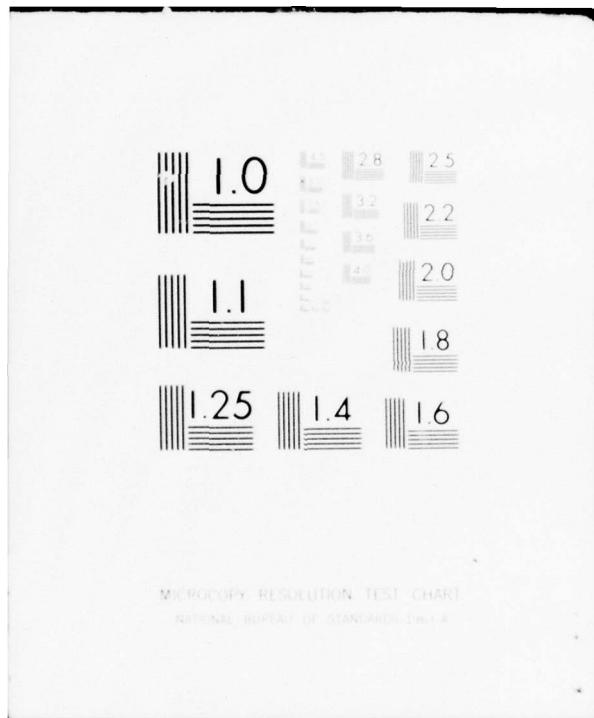
MISCELLANEOUS PAPER C-77-9

ACID ATTACK OF CONCRETE CAUSED BY SULFUR BACTERIA ACTION, PIEDMONT AND CLENDENING LAKES OUTLET TUNNELS MUSKINGUM WATERSHED, OHIO

by

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August 1977
Final Report

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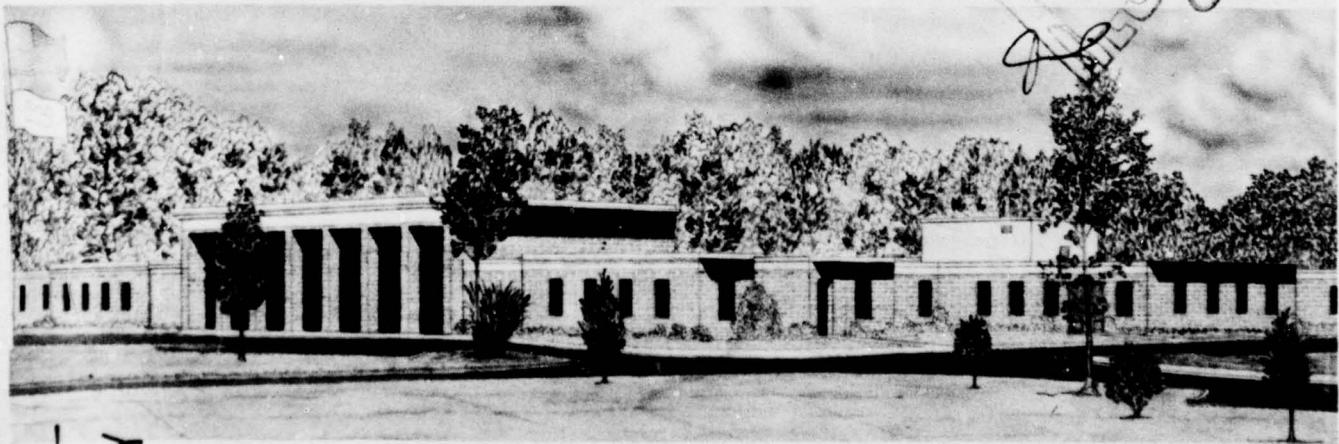
Prepared for U. S. Army Engineer District, Huntington
Huntington, West Virginia 25721

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER WES-MP- Miscellaneous Paper C-77-9	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) ACID ATTACK OF CONCRETE CAUSED BY SULFUR BACTERIA ACTION, PIEDMONT AND CLENDENING LAKES OUTLET TUNNELS, MUSKINGUM WATERSHED, OHIO.		5. TYPE OF REPORT & PERIOD COVERED Final Report
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Henry T. Thornton, Jr		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS U. S. Army Engineer Waterways Experiment Station Concrete Laboratory P. O. Box 631, Vicksburg, MS 39180		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS U. S. Army Engineer District, Huntington P. O. Box 2127 Huntington, WV 25721		12. REPORT DATE September 1977
		13. NUMBER OF PAGES 41
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Concrete deterioration	Sulfates	Corrosive process
Physical tests	Sulfides	Hydrogen sulfide
Chemical tests	Thermal stratification	Sulfuric acid
Bacteriological tests	Hypolimnion	Acid attack
Sulfur bacteria	Dissolved oxygen	

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This investigation was conducted to determine the cause of extensive deterioration of concrete above the flow line in the outlet tunnels of two lakes, and to provide guidance in the development of remedial repair schemes if necessary. The cement paste was being reduced to a "mush" consistency to depths up to 1-1/4 in. Anaerobic bacterial action was indicated by preliminary tests. The program of investigation included:

(Continued)

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20. ABSTRACT (Continued)

a. An extensive literature review on sulfur bacteria,

b. Collection of water samples, deterioration products, and concrete cores at each site;

c. Physical, chemical, and bacteriological testing of samples including identification of sulfate-reducing bacteria.

d. Obtaining other pertinent data from Huntington District.

Physical tests showed the original concrete to be of good quality and that some form of acid attack was in progress. Chemical tests revealed that the water contained high concentrations of sulfates and sulfides. Bacteriological tests confirmed that sulfate-reducing bacteria were present. Data furnished by Huntington District reveal that thermal stratification occurs during the summer causing almost complete depletion of dissolved oxygen at depths greater than 20 ft in both lakes providing an environment where sulfate-reducing bacteria are able to reduce the sulfates present in the water, producing hydrogen sulfide as a waste product. Conditions in the outlet tunnels meet the criteria for the deposition and proliferation of sulfur-oxidizing bacteria which produce sulfuric acid from the hydrogen sulfide. It is concluded that the deterioration is due to acid attack and is the final stage of a corrosive process caused by sulfur bacteria action. Attack by acid water is not indicated, since all the deterioration occurs above the line of normal flow.

Possible remedial measures including ventilation to remove the hydrogen sulfide, flushing the walls to remove the substrate, and raising the siphon intakes to draw water from above the sulfide-rich hypolimnion are offered for consideration for immediate implementation in both lakes. Further study will be necessary to determine the applicability of each of these remedial measures to the problem. It is also recommended that a long range program be formulated to deal with the problems produced by the high sulfate-sulfide concentrations in the lakes.

Attention is drawn to the fact that there may be other structures undergoing this type of deterioration, and that the corrosion may be proceeding undetected.

PREFACE

This investigation was authorized by DA Form 2544, No. E86-76-EF-02, dated 28 July 1975, and Change No. 1, dated 11 December 1975, from the U. S. Army Engineer District, Huntington, to the U. S. Army Engineer Waterways Experiment Station (WES). The investigation was performed by Concrete Laboratory (CL) personnel under the direction of Mr. Bryant Mather, Chief, CL, Mr. Leonard Pepper and Mrs. Katharine Mather, former Chief and Chief, respectively, of the Engineering Sciences Division, and Mr. John M. Scanlon, Chief, Engineering Mechanics Division. Mr. Alan D. Buck was responsible for the petrographic work and authored the "Petro-graphic Report" (Appendix A), and Mr. Tony B. Husbands, Chief, Chemistry and Plastics Branch, directed the chemical tests. Mr. Henry C. Thornton, Jr., was project leader of this investigation and the author of this report. The author is indebted to Messrs. Bill K. Colbert and Randall R. Williams of the Environmental Effects Laboratory for their periodic advice and assistance, and to Mr. Tom Plummer and Dr. George Kincaid, Huntington District, for their respective efforts in sample collection and testing at the sites, and supplying data pertinent to the investigation.

Special recognition is given to Dr. Thomas D. Wright, consultant to the Environmental Effects Laboratory, for his technical input and parti-cipation in conference activities that were essential to the successful completion of this study.

Directors of the WES during the conduct of this investigation and the preparation and publication of this report were COL G. H. Hilt, CE, and COL J. L. Cannon, CE. Technical Director was Mr. F. R. Brown.

CONTENTS

CONVERSION FACTORS, U. S. CUSTOMARY TO METRIC (SI)
UNITS OF MEASUREMENT

U. S. customary units of measurement used in this report can be converted to metric (SI) units as follows:

Multiply	By	To Obtain
feet	0.3048	metres
feet per second	0.3048	metres per second
pounds (force) per square inch	0.00689476	megapascals
inches	2.54	centimetres
acres	4046.856	square metres

ACID ATTACK OF CONCRETE CAUSED BY SULFUR BACTERIA ACTION

PIEDMONT AND CLENDENING LAKES OUTLET TUNNELS

MUSKINGUM WATERSHED, OHIO

PART I: INTRODUCTION

Background

1. Piedmont and Clendening Lakes are two of a system of projects
designed to provide flood control, recreation, and water conservation in
the Muskingum Watershed in southeastern Ohio (Photographs 1 and 2).
Piedmont and Clendening Lakes were constructed in 1937 and 1936, respec-
tively, and cover approximately 2300 and 1800 acres,* respectively.
Periodic inspection reports on these two projects in May of 1970 and
June of 1974, and interim inspections in December 1976, documented
observations of inordinate deterioration of the concrete in the outlet
tunnels. The observations made during the inspections pertaining to
the condition of the tunnel concrete are summarized below:

    a. Piedmont Tunnel. The tunnel liner during the initial
        inspection was reported to be in good condition with only
        a nominal amount of deteriorated concrete noted. However,
        the second periodic inspection revealed significant
        deterioration had occurred. In the transition area
        cement paste had been disintegrated and eroded leaving
        about 1 in. of aggregate exposed. The first 8 monoliths
        downstream of the transition displayed 3/4 in. to 1 in.
        of surface deterioration above the normal flow line and
        became discontinuous in the following 3 monoliths being
        generally limited to the crown area. When last observed
        during the interim inspection the concrete deterioration
        appeared to have become more extensive in depth and
        extent, both laterally and longitudinally.

    b. Clendening Tunnel. Conditions similar to those noted in
        the Piedmont Tunnel existed in Clendening except the
        latter appeared to be in a more advanced state. During
        the first periodic inspection approximately 1/8 in. of
        deteriorated concrete was detected in the crown area,

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* A table of factors for converting U. S. customary units of measure-
ment to metric (SI) units is presented on page 3.

extending 7 monoliths downstream of the transition. At the second inspection the depths had increased as much as 1 to 1-1/4 in. above the flow line and the deterioration had progressed to about 11 monoliths below the transition. In the transition area heavy aggregate exposure was exhibited similar to that of the Piedmont Tunnel. Additional deterioration was apparent during the interim inspection.

The periodic inspection reports contained petrographic reports on sample materials taken from the tunnels. These reports offered the postulate that anaerobic bacterial action may be in progress, and the sulfides being produced were reacting with the calcium compounds in the concrete.

2. In July 1975, the Concrete Laboratory (CL), U. S. Army Engineer Waterways Experiment Station (WES), was advised of these problems and requested to perform condition surveys of these projects including "studies and evaluations necessary to provide sufficient guidance in developing remedial repair schemes, if necessary." During subsequent communication Huntington District personnel requested that the CL determine if bacterial action was causing the problem, and consider the possibility of isolating and identifying them.

Scope

3. A preliminary study of the periodic inspection reports and other available information on the projects indicated problems of a unique nature and dictated some deviation from the methodology developed over the years for various types of condition surveys. The program of investigation adopted for this project was designed to provide information that would be relevant in answering the following questions:

   a. What is the mechanism causing the deterioration of the concrete in the outlet tunnels?

   b. Do the characteristics of the concrete reinforce this mechanism or contribute to the deterioration?

   c. What remedial measures are available and which of them are feasible and applicable in this particular situation?

The testing program and means by which data were collected are as follows:

   a. An extensive literature review into the cause, effect, and

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remedial measures concerning the mechanism of concrete corrosion caused by sulfur bacteria.

b. Sampling at each site, including water, deterioration products, and concrete cores.

c. Tests for physical properties of concrete, characteristics of deterioration products, water quality, and identification of sulfate-reducing bacteria.

d. Obtaining pertinent data and information from Huntington District.

PART II: LITERATURE REVIEW,

SULFUR BACTERIA

4. Most of the literature addressing the problem of deterioration of concrete by bacterial action evolved because of the great impact of this corrosive mechanism on concrete sewer systems. This is a serious problem and, as Rigdon and Beardsley[1] observed, occurs mainly in warm climates such as prevail in California, Australia, and South Africa.

Description and Life Cycle

5. Sulfur-reducing bacteria belong to the genus of bacteria that obtain the energy for their life processes from the oxidation of some element other than carbon, such as nitrogen, sulfur, or iron.[1] Some of them are able to reduce the sulfates which are present in natural waters and produce hydrogen sulfide as a waste product. These bacteria, as stated by Wetzel,[2] are anaerobic. Another group takes the reduced sulfur and oxidizes it back to sulfuric acid. The genus Thiobacillus is the sulfur bacteria which is most destructive to concrete. It has a remarkable tolerance of acid. Concentrations of sulfuric acid as great as 5 percent do not completely inhibit their activity.

The Corrosion Process

6. Rigdon and Beardsley[1] and Forrester[3] described the process of corrosion of concrete by bacterial action in almost identical terms. Sulfur bacteria are likely to be found wherever warmth, moisture, and reduced compounds of sulfur are present. Certain conditions must prevail before the sulfur bacteria can become established on the concrete surface and begin the process of corrosion. Sufficient moisture must be present to prevent the desiccation of the bacteria. There must be adequate supplies of hydrogen sulfide, carbon dioxide, nitrogen compounds, and oxygen. In addition, soluble compounds of phosphorus, iron, and other trace elements must be present in the moisture film.

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7. Newly made concrete has a strongly alkaline surface with a pH of about 12. No species of sulfur bacteria can live in so alkaline an environment. Therefore the concrete is temporarily free from bacterially induced corrosion. Natural carbonation of the free lime by the carbon dioxide in the air slowly drops the pH of the concrete surface to nine or less. At this level of alkalinity the sulfur bacteria Thiobacillus thioparus, using hydrogen sulfide as a substrate, generate thiosulfuric and polythionic acid. The pH of the surface moisture steadily declines, and at a pH of about five the Thiobacillus concretivorus begin to proliferate and produce high concentrations of sulfuric acid, dropping the pH to a level of two or less. The destructive mechanism in the corrosion of the concrete is the decomposition of the calcium silicates and aluminates in the cement paste by the sulfuric acid.

Effects of the Corrosion Process

8. Reference 4 cites examples of corrosion damage such as: a steel rising main which dissolved in 18 months; concrete trunk sewers stripped beyond the reinforcement within 10 years; numerous cases of asbestos cement pipes (some with protective coatings) eaten away above the sewage line in 5 to 10 years; machinery and fittings being attacked-- in one case, cast iron penstocks at a pumping station are reported to have totally disappeared in 6 to 7 years. All this damage was attributed to bacterial action of one type or other. Woods[5] reported a disposal well in Texas suddenly developed a high head after previously operating under vacuum; a fresh-water well in California suddenly caused plugged filters ahead of a demineralizer unit (the clogging material was identified as elemental sulfur); a water supply system in Kansas suddenly became fouled with iron deposits; deionizing equipment in Arizona became ineffective because of resin poisoning due to leaching of iron from the formation. Each malfunction resulted from some type of bacterial action.

Remedial Measures

9. Parker[6] outlined 17 ways in which the corrosion process may be interrupted and result in the damage being halted.

Discharge of sulfides

Eliminate trade wastes containing sulfides.

Hydrogen sulfide generation

a. Reduce the concentration of sulfates.

b. Partially purify by sedimentation, etc.

c. Dose with chemicals to raise oxidation-reduction potential.

d. Aerate by forcing air into bottom end of rising mains.

e. Treat with chlorine to oxidize any hydrogen sulfide present and to prevent further generation.

f. Remove slime and silt where hydrogen sulfide is generated.

g. Increase the rate of flow.

Emission of hydrogen sulfide

a. Reduce turbulence of flow.

b. Precipitate hydrogen sulfide by adding heavy metal salts.

c. Add alkalies to reduce the undissociated hydrogen sulfide.

d. Run sewer full, thereby eliminating atmosphere.

Rate of hydrogen sulfide fixation on concrete

a. Ventilate to remove hydrogen sulfide and lower humidity.

b. Flush walls periodically above waterline to eliminate environment of proliferation.

c. Use acid resistant concrete.

d. Dose atmosphere with ammonia to neutralize acid.

e. Provide protective lining for concrete.

Description

10.   The outlet tunnel at Piedmont Lake is 670.5 ft long, 10 ft in diameter, and has a grade of 0.26 percent.   The Clendening Lake tunnel is 498 ft long, 8 ft in diameter, and has a grade of 0.372 percent.   At the downstream end of each tunnel there is a rising invert with a 2-ft wide slot (Photograph 3).   These rising inverts back water up in the tunnels when operating at normal water release.   The back-up water depth is approximately 3 ft at Clendening and 4 ft at Piedmont.   After the water flows over the invert or through the slot, it passes through the stilling basin and continues downstream (Photograph 4).   About 50 percent of the time, during a typical year, water from the reservoir enters the tunnels through siphons which function to maintain minimum pool (approximately 34 ft of water) in the reservoirs.   Although the siphoning usage is controlled at higher elevations, the water drawn from the reservoir by the siphons comes from very near the bottom.

Condition

11.   The water in the stilling basins and in the streams at both projects was of a pale blue color with a white foam floating on it (Photographs 3 and 4).   The lines of normal flow were clearly discernible by the water marks on the sides of the tunnels.   About one-third of the way into the tunnels the deterioration became evident above the normal flow lines (Photograph 5).   In the vicinity of the gate-transition areas the deterioration was more pronounced (Photograph 6).   The conditions inside the tunnels were very similar to those described by Parker[6] when relating to acid attack in concrete sewers.

12.   Before access to the tunnels was granted (September), the air inside was checked for methane, hydrogen sulfide, and other toxic gases by personnel from the Mine Enforcement Safety Administration.

Hydrogen sulfide gas was present at a level of five parts per million in the air in Clendening tunnel. Although this is not considered to be a hazardous level, the presence of hydrogen sulfide gas in the tunnel was noteworthy. No other toxic or corrosive gases were found in either tunnel. However, operations personnel at both sites reported that during July, August, and September a very strong hydrogen sulfide odor prevails. Piedmont personnel reported that during this period the white-painted signs near the tunnel portal turn black, and that the black film disappears in the fall when the odor subsides. Piedmont tunnel had 3 to 4 hr to ventilate prior to measurements for toxic gas detection.

PART IV: SAMPLING, TESTS AND RESULTS, OTHER DATA

Sampling

Water samples

13. Water samples, deterioration products, and concrete cores were taken from each tunnel in September 1975 to provide specimens for physical and chemical tests. Three water samples were taken from each tunnel. In September 1975, an unstabilized sample for sulfate tests and a sample stabilized with zinc acetate for sulfide tests were taken from each tunnel. In January 1976, another sample was taken from each tunnel to test for sulfate-reducing bacteria. This interim provided time for acquisition of equipment and preparations for performing the tests. All water samples were taken as near to the gates as possible in order to avoid contamination and aeration.

Deterioration products

14. In September 1975, two samples of deterioration products were scraped from the roof of each tunnel in the severely damaged areas. One sample from each tunnel was returned to the laboratory as scraped from the roof; the other was added to water containing zinc acetate.

Concrete cores

15. Two 4-in. diameter concrete cores were taken from each tunnel in September 1975. One core came from near the longitudinal midpoint of each tunnel, and one came from near the sluice gates in each tunnel. All cores were taken from a height of about 3 ft up on the tunnel walls.

Tests and Results

Physical tests

16. Velocity measurements and unconfined compressive strength tests were performed on the concrete cores returned to the CL in accordance with CRD-C 51-72[7] and CRD-C 27-65.[7] The results of the velocity measurements and strength tests are given in Table 1. The average velocity and strength of the Piedmont cores were 15,180 fps and 9,515 psi,

respectively, with very little variation between the upstream core (P-1) and the midpoint core (P-2). There were two pieces of each core from Clendening Tunnel. The average velocity and strength for the upstream (C-1) cores were 15,105 fps and 7,745 psi. The midpoint cores averaged 15,150 fps and 6,245 psi. The Piedmont cores were considerably stronger than those of Clendening, but the velocities were all very nearly the same. These data look generally normal and indicate no reason to suspect poor concrete quality.

17. Velocity measurements were also made through the piers located just downstream of the gates in each tunnel. These piers were in the splash area where water enters the tunnels and exhibited considerable loss of mortar and aggregate where the deterioration product had been washed away. The surfaces were rough due to exposed aggregate, but did not prohibit velocity measurements. Two readings were made in each pier in each tunnel. The results are given in Table 2 along with locations and path lengths. One velocity on pier No. 2, Piedmont, was low, but this is probably caused by surface irregularities. The strength of the concrete represented by velocities in Table 2 was probably 6,000 psi and above.

18. Appropriate petrographic methods were used to test the concrete cores and deterioration products from the tunnels. A complete petrographic report is attached as Appendix A. It contains a detailed description of the cores and the deterioration products, the locations from which they came, and an explanation of test procedures. Some general findings stated in the report are:

 <u>a</u>. The mechanism of deterioration is not sulfate attack because there was no ettringite present (a reaction product of sulfate attack), and sulfate attack would be more widespread.

 <u>b</u>. There are indications of some form of acid attack because the acid-soluble carbonates in the aggregate are missing.

 <u>c</u>. Attack by acid water is not indicated, since all the deterioration occurs above the waterline.

Chemical tests

19. Tests for sulfate content in the water of the two outlet

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tunnels using the turbidimetric method[8] revealed levels of 499 mg/ℓ at Piedmont and 311 mg/ℓ at Clendening. Sulfides were shown by tests (228 A)[9] to be present in Piedmont and Clendening waters in the amounts of 11.5 mg/ℓ and 7.2 mg/ℓ, respectively. The test for sulfate-reducing bacteria, D 993-58,[8] which entails growing the bacteria in a culture medium, was positive for the Piedmont Lake sample. The samples were collected in January, during the mixing cycle of the lake, so it is not surprising that the Clendening sample was negative.

Other Data

20. Huntington District furnished water quality data from samples taken over the years from various locations in Piedmont and Clendening Lakes which included water temperature, pH, dissolved oxygen content, and sulfate content at various water depths. The pH and sulfate content taken from the composite statistical summaries for the two lakes are as follows:

| | pH | | | Sulfate, mg/ℓ | | | Reporting |
	Mean	Max	Min	Mean	Max	Min	Period
Piedmont*	7.9	8.9	7.1	526	700	420	7/73-9/76
Clendening**	7.8	9.2	6.6	314	431	250	8/74-9/76

  *   Maximum depth 30 ft.
 ** Maximum depth 35 ft.

21. The fact that the overall thermal structure and dynamics of some lakes undergo seasonal changes (as discussed by Reid),[10] is relatively well known. During winter the temperature of the water is relatively uniform from surface to bottom due to surface water becoming dense, moving to the bottom and displacing water which has become relatively warmer. During the summer this natural mixing diminishes and any vertical heat transfer must be accomplished, mainly, by wind action.[10] Thermal stratification can develop, causing a thermal resistance to mixing, which ultimately can lead to the development of a thermocline. A thermocline is defined as "the plane of maximum rate of decrease in temperature." In many lakes the zone below the thermocline, designated the hypolimnion, becomes devoid of dissolved oxygen and high in carbon dioxide.[10] In the fall, normal mixing due to increased relative density of surface water

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starts to break down the stratification. When this occurs, vertical circulation is restored, vertical temperature gradients diminish, and dissolved oxygen becomes more evenly distributed from surface to bottom of the lake. A review of the water quality data indicates that seasonal conditions similar to those just described exist at Piedmont and Clendening lakes.

22. Tables 3 and 4 give the temperature and dissolved oxygen profiles with water depth for Piedmont and Clendening lakes, respectively. July data for 1973 through 1976 are compared to show typical conditions during the summer months at Piedmont. November 1973 and September 1976 data are given to show how conditions begin to change in the fall. Data given for Clendening Lake include days in August of 1974, 1975, and 1976, and September 1976. The July 1976 and September 1976 data, Piedmont Lake, are plotted in Figures 1 and 3, respectively. August 1976 data (no tabulation available) are plotted in Figure 2. Clendening Lake data from June, July, August, and September 1976 are plotted in Figures 4-7. These data were obtained from collection points in the deep parts of the lakes near the dams, PES20002 at Piedmont, CLB20002 at Clendening, and show that dissolved oxygen depletion occurs in the summer months at depths of 20 to 22 ft and below at Piedmont, and at depths of around 15 ft and below at Clendening Lake. Plots of data (Figures 3 and 7) collected in the early fall illustrate the return of uniform distribution of temperature and dissolved oxygen with depth due to natural cold-weather mixing action. A study of all the data furnished by Huntington District indicates that dissolved oxygen depletion begins in Piedmont Lake in early June and lasts into September, when stratification starts to break down. There were insufficient data to determine when this cycle starts at Clendening, but mixing action starts in September.

PART V: DISCUSSION

Concrete Quality

23. The results of the velocity measurements, unconfined compressive strength tests, and petrographic examinations of the concrete cores indicate that the quality of the concrete in the outlet tunnels at Piedmont and Clendening Lakes is good, and that the mechanism causing the deterioration did not originate from either deleterious materials or reactions within the concrete. Velocity measurements made through the concrete piers near the sluice gates in each tunnel indicate that the quality of the concrete in the piers in each tunnel is as good as that of the concrete cores from the respective tunnels.

Water Quality

24. The pH of the water at Piedmont and Clendening Lakes does not contribute to the deterioration of the concrete in the outlet tunnels. However, the sulfate levels of approximately 500 mg/ℓ (Piedmont) and 300 mg/ℓ (Clendening) and sulfide levels of 11.5 mg/ℓ (Piedmont) and 7.2 mg/ℓ (Clendening) are high and could lead to deterioration of environmental quality downstream. Some sources of sulfur compounds to natural waters are rocks, fertilizers, atmospheric transport, and organic wastes.[2] The relative contributions of these sources vary with the regional lithology, agricultural application of sulfate-containing fertilizers, the proximity of atmospheric sources, and the type of industrial wastes dumped into inflowing streams. Paper-producing industries and strip-mining operations are common sources of sulfate-rich by-products. A brief study of available information performed by the water quality staff, Huntington District, indicates that strip-mining operations are the major contributors of sulfate to Piedmont Lake.

25. The high concentrations of hydrogen sulfide in Piedmont and Clendening Lakes during the summer are apparently the result of the decomposition of organic matter by bacterial metabolism. The summer

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stratification of the water and subsequent depletion of dissolved oxygen in the hypolimnion provide the required environment for the bacterial reduction of sulfates and release of hydrogen sulfide. Stuiver[11] reports that the rate of reduction of sulfates in anoxic regions, or regions partly devoid of oxygen, is 10 times faster than in the fully aerobic region. He also found that horizontal diffusion was sufficient to transport sulfates to the surrounding sediments, thereby providing organic substrates for bacterial metabolism in the hypolimnion and sediments. The sulfide is stored in the water and in the sediment. During a 4-month period, as much as 1 mg was stored per cm^2 of sediment in one pond. The escape of hydrogen sulfide to the atmosphere by diffusion or gas bubbles was very small.

26. With accumulations of hydrogen sulfide on and near the bottoms of the lakes, all that is necessary to start the corrosion process is to get the hydrogen sulfide into the crowns of the tunnels. This is obviously accomplished by the normal operation of the siphons and gates, since they both draw water from near the bottom of the lakes. As the water enters the tunnels the turbulence causes hydrogen sulfide to be released into the tunnel air and the corrosion process described in paragraphs 6 and 7 begins. Factors that substantiate these postulations are:

 <u>a</u>. Acid water is not the deteriorating agent of the concrete.

 <u>b</u>. The sulfate-rich, oxygen-free hypolimnion during summer stratification provides the environment for bacterial proliferation.

 <u>c</u>. The sulfide contents of the water samples were very high.

 <u>d</u>. The water entering the tunnels is drawn from the hypolimnion where hydrogen sulfide is stored.

 <u>e</u>. Sulfate-reducing bacteria were cultured and identified from a sample of Piedmont Lake water.

 <u>f</u>. The conditions in the tunnels are favorable for bacteria proliferation and the damage in the tunnels is similar to that described in the literature.

 <u>g</u>. Physical tests show the intact concrete to be of good quality, and also indicate that acid attack is the deterioration mechanism.

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PART VI: REMEDIAL MEASURES

Long Range

27.   The most desirable remedy would be one which would eliminate
the entire process.   To accomplish this, the high concentrations of sul-
fates in the lakes must be eliminated.   Finding and/or eliminating the
sulfate source or sources may be impossible or impractical, especially
if strip mining operations are the major contributors.   The next point
of interruption of the process is reducing or eliminating the hydrogen
sulfide generation or oxidizing it by chemical treatment as it is gen-
erated.   Dosing with chemicals can be costly and problematic.   Of all
the possibilities, aeration or **destratification** seems to be the most
practical means of inhibiting hydrogen sulfide production in the
lakes.

28.   *Circulation and aeration by mechanical means is a common*
method of increasing the use potential of lakes.   The basic objective is,
usually, to improve the dissolved oxygen conditions.[12, 13]   The two cate-
gories of aeration are total aeration and hypolimnetic aeration.   Total
aeration effects complete destratification and hypolimnetic aeration
brings deep water up for oxygenation and returns it without disrupting
thermal stratification.   Other techniques used are deepening, dredging,
drawdown and sediment consolidation, harvesting, etc.[12]   There are, of
course, problems associated with each technique.

Immediate

29.   There are a variety of ways to interrupt the concrete deteriora-
tion process in the tunnels.   Of those mentioned in paragraph 9, ventila-
tion and wall flushing seem to be the most practical and, probably, the
most economical.   Ventilation could be accomplished by forcing air through
the entire lengths of the tunnels, or by venting with a series of shafts
bored through the crown, or both.   Some experimentation would be necessary
to determine the flow of air through the tunnel or the number of vents

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that would be required to effectively reduce the deterioration. The effectiveness of flushing the walls to remove the substrates necessary to sustain bacteria metabolism would also have to be investigated.

30. Another measure that should be given serious consideration is that of raising the siphon intake elevation. Looking at the plotted data it seems that siphoning the water from Piedmont Lake from the upper 20 ft, and from Clendening Lake above 15 ft could possibly eliminate the injection of hydrogen sulfide into the tunnels through the siphons. These levels may change gradually during the summer, but periodic samples of water could serve as a depth guide. Gate operation would still inject sulfide, but minimal operation may reduce the sulfide to a harmless level. It may be necessary to supplement shallow siphoning with some degree of ventilation.

31. The measures outlined in the two preceding paragraphs may serve to decrease the effects of the corrosive process in the tunnels, but the causative factors will remain in the lakes if remedial measures are not implemented. The sulfate and sulfide concentrations will remain high, and the semiannual periods of dissolved oxygen depletion caused by thermal stratification will continue. Although an overall oxygenation problem may never arise, the potential for injecting water with high sulfate-sulfide contents into the fresh-water stream will remain.

PART VII: CONCLUSIONS AND RECOMMENDATIONS

32. After an evaluation of the summation of test results and other
accumulated data and information pertaining to this investigation, it is
concluded that the deterioration of the concrete in the outlet tunnels of
Piedmont and Clendening Lakes is most likely due to acid attack and is
the final stage of a corrosive process caused by sulfur bacteria action.
The process starts with the production, by bacteria, of hydrogen sulfide
from the sulfate-rich water in the lake, and by organic decomposition in
the sediment. The hydrogen sulfide passes through the siphons and gates
and is released into the atmosphere in the gate-transition area due to
the turbulence of the water. The hydrogen sulfide collects in the crown
of the tunnel in concentrated amounts for some distance down the tunnel,
is oxidized into sulfuric acid by concretivorus bacteria, and the con-
stituents of the cement paste are decomposed by the acid. Physical
mechanisms such as freezing and thawing and hydraulic washing probably
aid the corrosive process.

33. It is recommended that remedial measures such as ventilation,
flushing, or raising siphon intakes be implemented as soon as determina-
tions have been made concerning the applicability of each measure to the
problem. Considering the emphasis placed on energy conservation and
increased productivity within most energy sources, it seems unlikely that
strip-mining operations will cease or diminish in the near future. There-
fore, if strip-mining operations are the major contributors of sulfates
to Piedmont and Clendening Lakes, the corrosion process caused by the
action of sulfur bacteria will have to be interrupted at some point after
the sulfates have entered the lake water.

34. Because of its subtle nature, this type of problem could go
undetected for many years. For this reason, and because of the potential
impact on structural integrity and environmental considerations, it seems
appropriate to point out that there may be other structures deteriorating
that have gone undetected. Rigdon and Beardsley[1] observed that most sewers
in the southern United States meet the conditions for bacteria prolifera-
tion. The results of this investigation indicate that this problem is not
necessarily restricted to certain structures or regions.

20

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Table 1

Piedmont – Clendening Lakes
Results of Laboratory Tests for
Pulse Velocity and Compressive Strength
of Concrete Cores

Core No.	Velocity, fps	Compressive Strength, psi
P-1	15,235	9,550
P-2	15,120	9,480
Average	15,180	9,515
C-1 (top)	15,060	7,490
C-1 (bottom)	15,150	8,000
Average	15,105	7,745
C-2 (top)	14,660	6,330
C-2 (bottom)	15,635	6,160
Average	15,150	6,245

Table 2

Piedmont - Clendening Lakes

Results of Pulse Velocity Measurements on Piers

Pier No.	Reading Location*	Path Length ft	Velocity fps	Average Pier Velocity, fps
	Piedmont Lake			
1	6 ft upstream from nose	2.9	15,185	
1	10 ft upstream from nose	2.1	15,110	15,150
2	2 ft upstream from nose	2.4	14,460	
2	6 ft upstream from nose	1.4	13,335	13,900
3	6 ft upstream from nose	2.9	15,590	
3	10 ft upstream from nose	2.1	14,685	15,140
	Clendening Lake			
1	4 ft upstream from nose	3.2	15,460	
1	7 ft upstream from nose	2.2	14,865	15,160
2	4 ft upstream from nose	3.2	13,975	
2	7 ft upstream from nose	2.2	14,665	14,320

* All reading locations were 4 ft from the floor, vertically.

Table 3
Piedmont Lake Temperature
and Dissolved Oxygen Data

Water Depth ft	Temperature deg C	Dissolved Oxygen mg/ℓ
	31 July 1973	
0	27.0	8.5
5	26.9	8.6
10	25.8	8.1
15	25.3	7.2
20	23.8	0.4
25	19.0	0.2
	10 July 1974	
0	28.0	9.6
10	24.9	11.4
20	21.0	3.8
30	15.1	0.1
	13 July 1975	
0	26.5	10.3
5	26.1	10.7
10	25.9	10.6
15	25.5	9.8
17	23.5	5.0
20	22.1	1.6
22	20.1	0.1
25	17.0	0.1
27	14.5	0.1
30	13.3	0.1

(Continued)

Table 3 (Continued)

Water Depth ft	Temperature deg C	Dissolved Oxygen mg/ℓ
	15 July 1976	
0	25.2	8.0
2	25.1	8.1
4	24.9	8.2
6	24.1	8.0
8	23.8	7.7
10	23.7	7.6
12	23.5	7.4
14	23.4	7.2
16	23.2	6.9
18	23.0	6.8
20	22.4	5.6
22	20.4	0.3
24	18.7	0.3
26	16.9	0.3
	29 November 1973	
0	8.8	11.0
5	9.1	10.6
10	9.2	10.4
15	9.5	10.2
20	9.4	10.0
	22 September 1976	
0	20.3	7.0
2	20.3	7.0
4	20.3	7.0
6	20.3	7.0
8	20.2	7.0
10	20.1	7.0

(Continued)

Table 3 (Concluded)

Water Depth ft	Temperature deg C	Dissolved Oxygen mg/ℓ
22 September 1976 (Continued)		
12	20.1	7.0
14	20.0	7.0
16	20.0	6.9
18	20.0	6.8
20	20.0	6.5
22	20.0	6.2
24	19.7	6.6

Table 4

Clendening Lake Temperature

and Dissolved Oxygen Data

Water Depth ft	Temperature deg C	Dissolved Oxygen mg/ℓ
20 August 1974		
0	29.5	10.8
5	25.8	12.7
10	24.4	5.8
15	23.0	0.2
20	20.4	0.2
30	16.7	0.2
34	14.8	0.2
9 August 1975		
0	25.7	9.5
2	24.9	9.9
5	24.8	9.3
7	24.7	9.1
10	24.3	4.7
12	24.0	0.7
15	22.2	0.0
17	20.8	0.0
20	19.0	0.0
22	17.1	0.0
25	16.0	0.0
27	14.8	0.0
30	13.8	0.0
32	13.4	0.0
35	13.3	0.0
18 August 1976		
0	25.5	8.4
2	25.5	8.4

(Continued)

Table 4 (Continued)

Water Depth ft	Temperature deg C	Dissolved Oxygen mg/ℓ
18 August 1976 (Continued)		
4	25.1	8.4
6	24.9	8.6
8	23.3	8.0
10	22.9	3.6
12	22.6	1.9
14	22.5	0.8
16	22.2	0.5
18	21.9	0.4
20	21.5	0.4
22	20.9	0.3
24	20.4	0.3
26	20.0	0.3
28	19.4	0.3
30	17.6	0.3
32	16.5	0.3
22 September 1976		
0	19.9	3.3
2	20.0	3.2
4	20.0	3.2
6	20.0	3.2
8	20.0	3.2
10	20.0	3.2
12	20.0	3.2
14	20.0	3.2
16	20.0	3.2
18	20.0	3.2
20	20.0	3.0
22	20.0	3.0

(Continued)

Table 4 (Concluded)

Water Depth ft	Temperature deg C	Dissolved Oxygen mg/ℓ
22 September 1976 (Continued)		
24	20.0	2.9
26	19.8	2.2
28	19.0	0.5
30	17.6	0.4
32	16.8	0.4
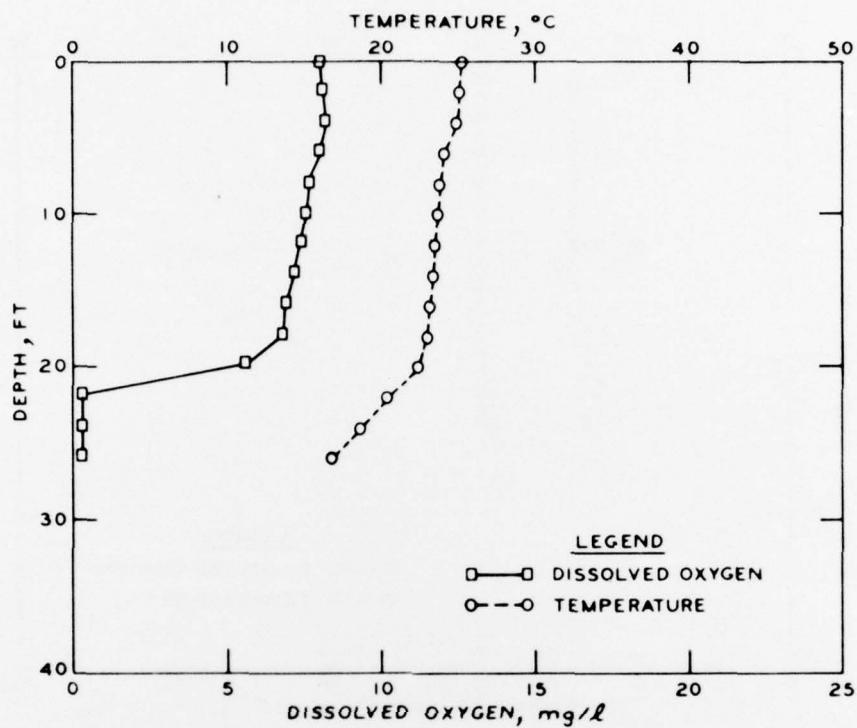
Figure 1. Piedmont Lake, 15 July 1976
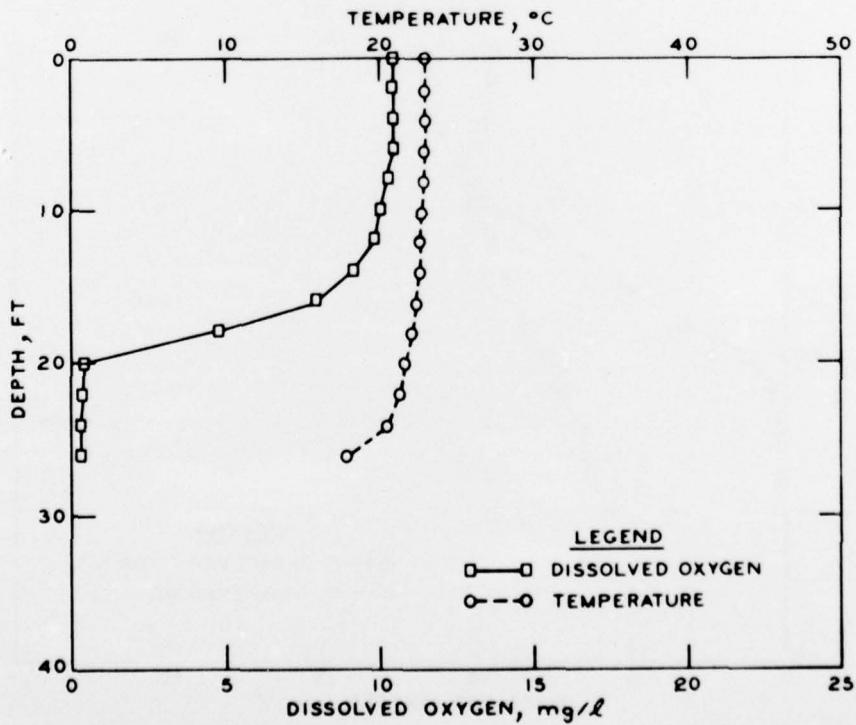
Figure 2. Piedmont Lake, 19 August 1976
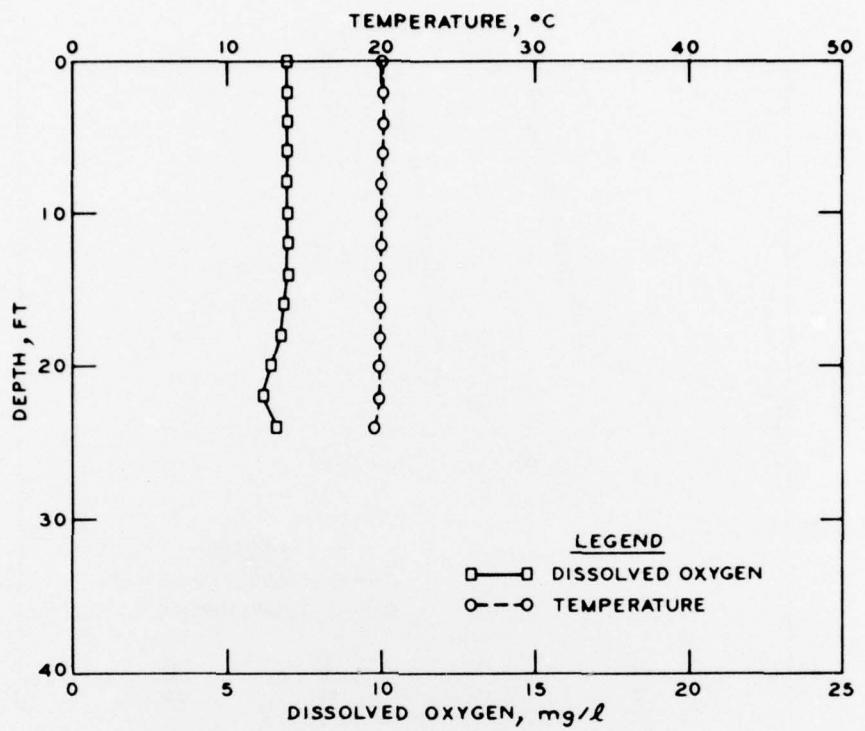
Figure 3.   Piedmont Lake, 22 September 1976
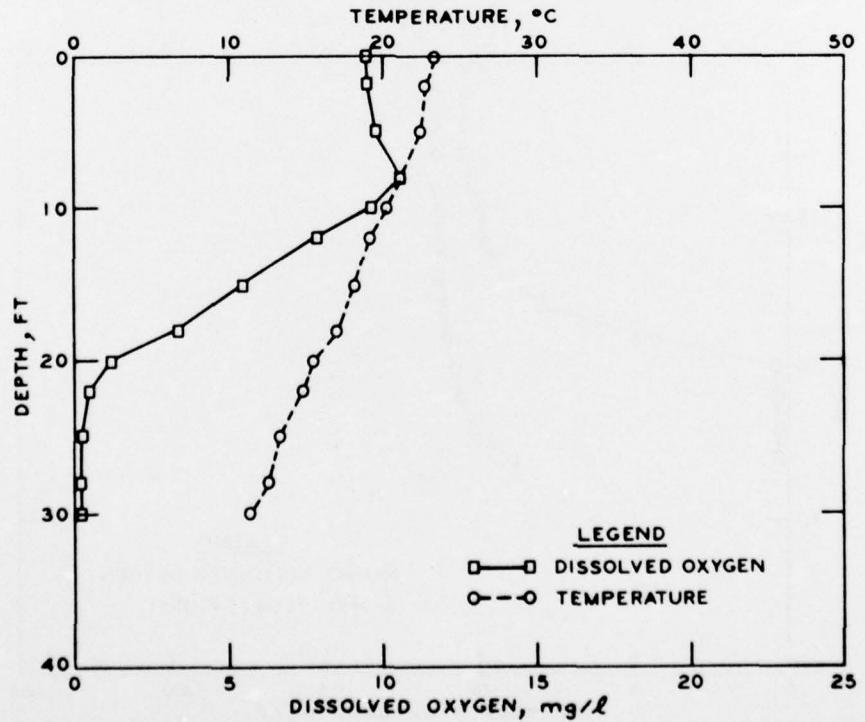

Figure 4.   Clendening Lake, 9 June 1976
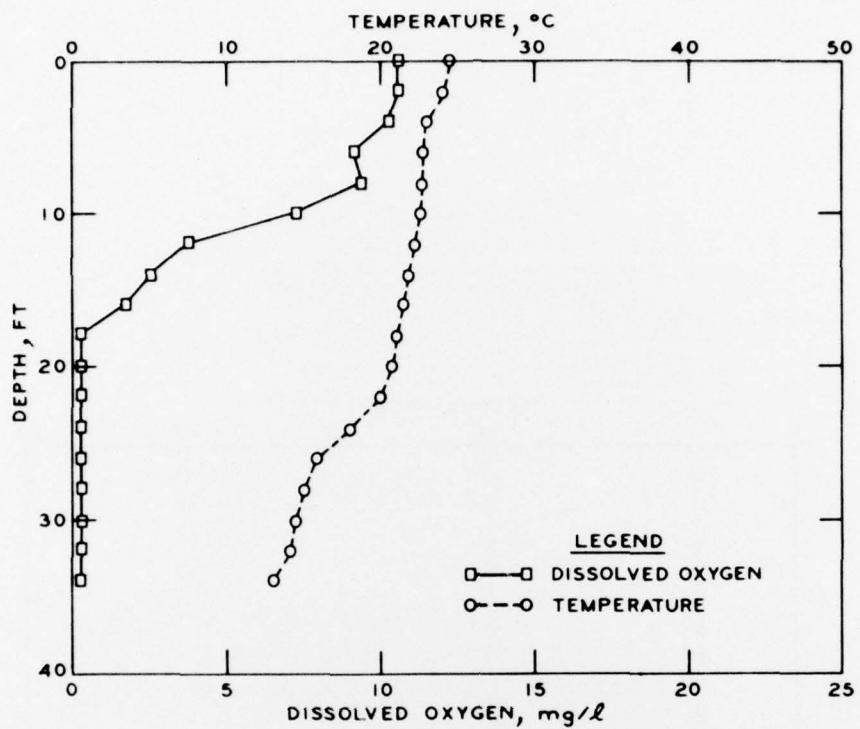
Figure 5.   Clendening Lake, 14 July 1976
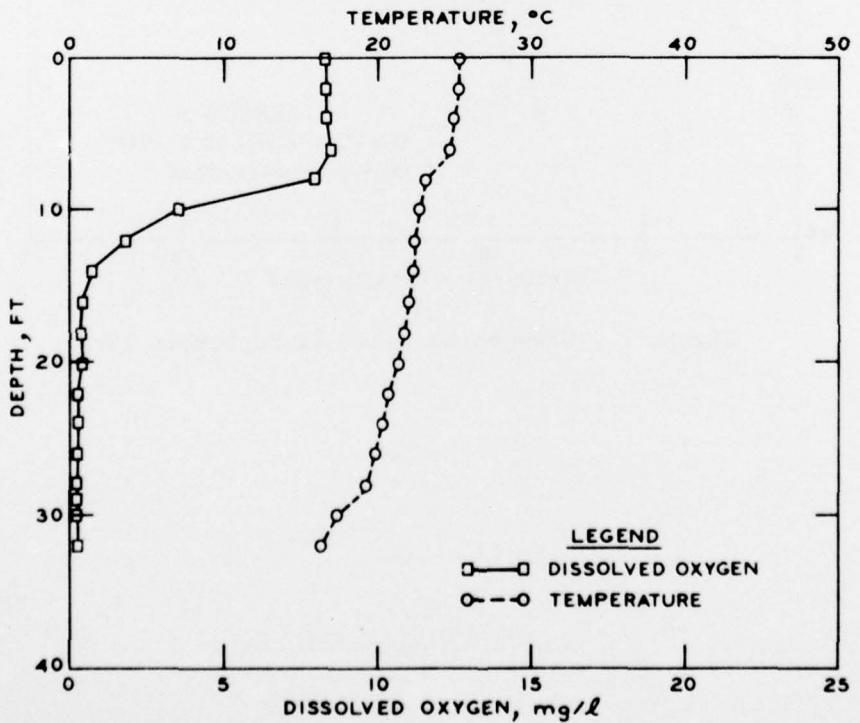
Figure 6.   Clendening Lake, 18 August 1976
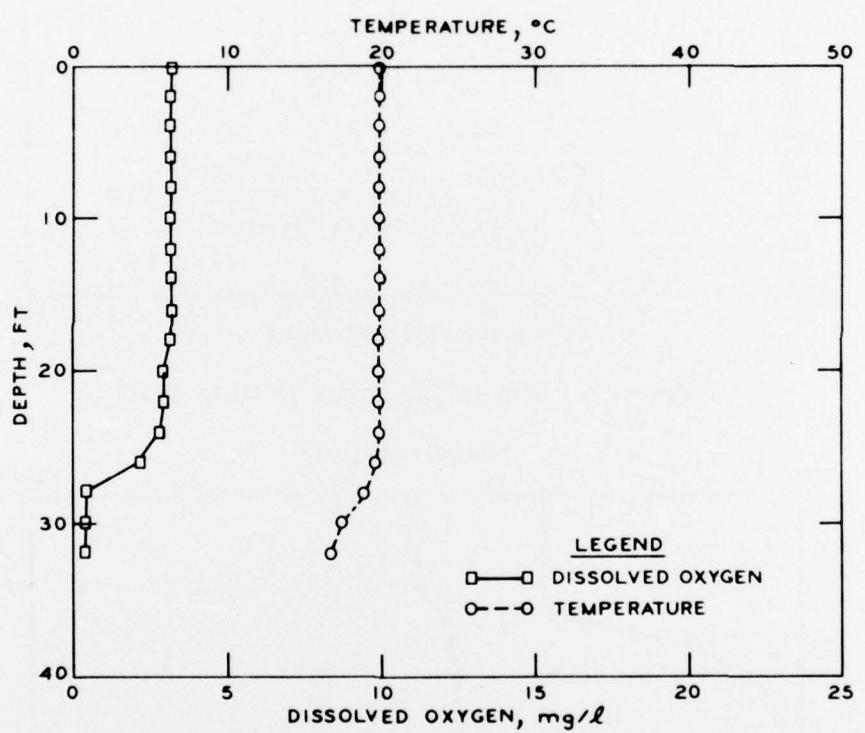
Figure 7. Clendening Lake, 22 September 1976
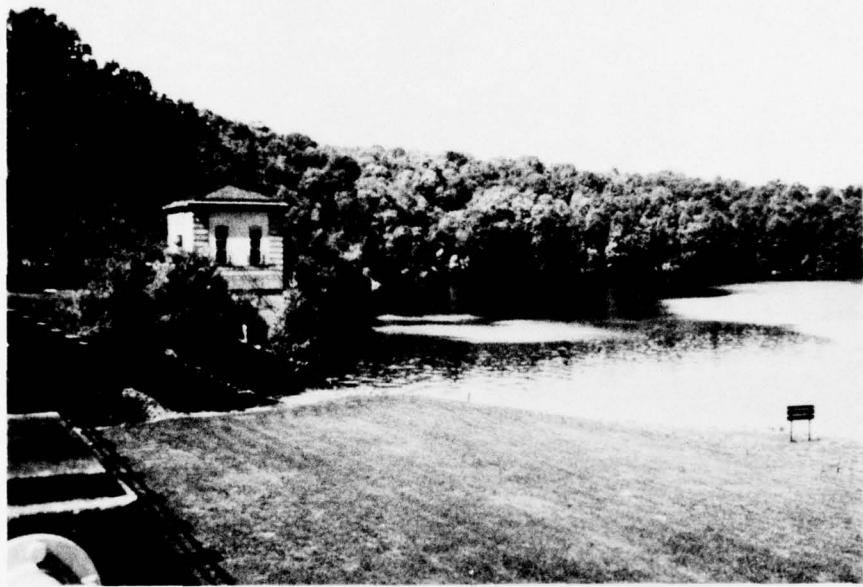
Photograph 1. Clendening Lake

Photograph 2. Clendening Lake

Photograph 3.   Clendening Lake, view showing rising
invert with slot

Photograph 4.   Clendening Lake, view downstream of
stilling basin
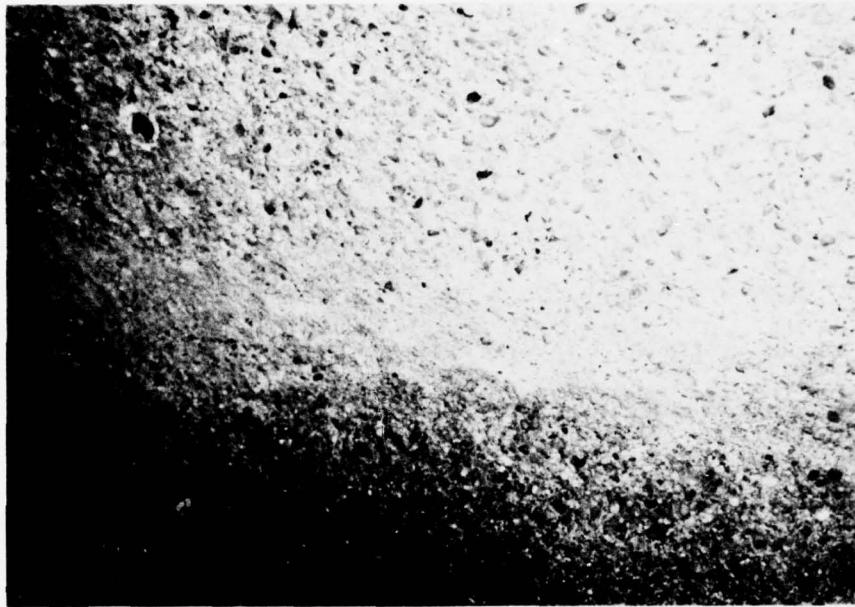
Photograph 5.   Clendening Lake, deterioration
above normal flow line
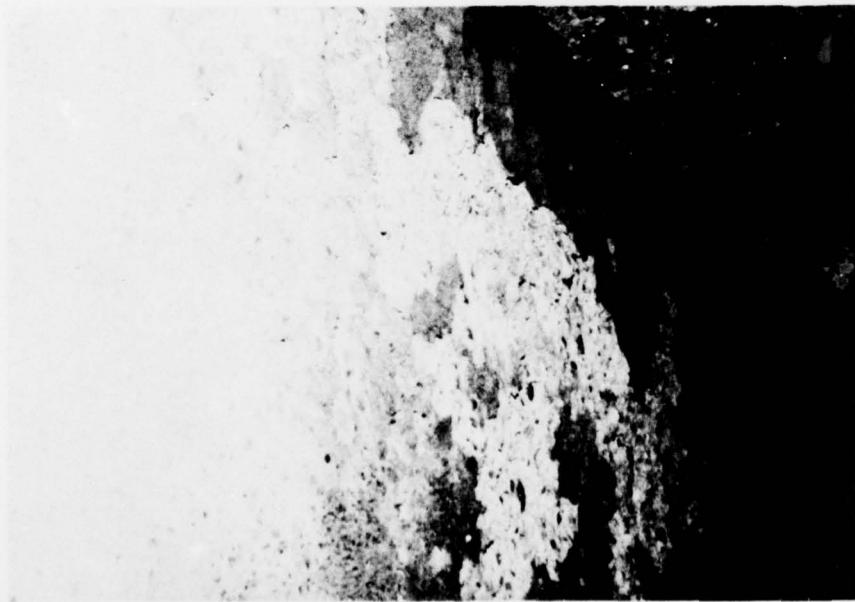
Photograph 6.   Clendening Lake, deterioration near gates

Corps of Engineers, USAE Waterways Experiment Station	APPENDIX A Petrographic Report	Concrete Laboratory P. O. Box 631 Vicksburg, Mississippi
Project Tests of Deteriorated and Intact Concrete from Outlet Tunnels, Clendening and Piedmont Lakes		Date 11 November 1975 ADB

Background

1. It was observed by personnel of the U. S. Army Engineer District, Huntington, that some of the concrete in the outlet tunnels at Clendening and Piedmont Lakes was deteriorating into a soft mushy material. The age of the structures is approximately 40 years. The condition seems to have started during the past 5 years and is largely confined to concrete that is at or just above the normal waterline in these tunnels. It had been postulated that the damage might be due to the action of anaerobic bacteria on sulfates in the water. This mechanism is described by Parker.[1] In this reaction, bacteria in the water reduce sulfur to hydrogen sulfide gas which escapes into the air above the water. Other bacteria on substrates above the waterline then oxidize this gas to sulfuric acid, and the acid destroys the concrete above the waterline.

2. The work described in this report was done to determine the composition of the deteriorated concrete and to compare it to intact concrete from the same tunnels.

Samples

3. The samples described below were received in September 1975:

CL Serial No. HUN-8 CON-	Field Data		
	Sample	Source	Description
1(A)	C-1	Clendening Lake	Intact concrete core from upstream end of outlet tunnel
1(B)	C-2	Clendening Lake	Intact concrete core from midpoint of same tunnel
1(C)	Scrapings	Clendening Lake	Soft, deteriorated concrete from a length of ceiling in same tunnel
2(A)	P-1	Piedmont Lake	Intact concrete core from upstream end of outlet tunnel
2(B)	P-2	Piedmont Lake	Intact concrete core from midpoint of same tunnel
2(C)	Scrapings	Piedmont Lake	Soft, deteriorated concrete from a length of ceiling in same tunnel

The two Piedmont cores had been identified as C-1 and C-2 in the field; they were redesignated P-1 and P-2 in the laboratory to avoid confusion

with the Clendening cores. All of the cores were 4 in. in diameter; they were taken at or below the usual waterline in the tunnels.

Test procedure

4. After the cores were logged, the ends were sawed off to facilitate compressive strength and velocity tests.

5. The cores and the soft deteriorated concrete were examined with a stereomicroscope.

6. The opposite end pieces of each core were crushed and blended to provide a composite sample of each core. These samples were then separated over a 150 μm (No. 100) sieve.

7. The soft, deteriorated samples were allowed to dry and were then separated over a 150 μm sieve. The intent of separating these samples and the crushed concrete cores over the 150 μm sieve is to obtain a concentrate of cement paste in the material passing the 150 μm sieve.

8. Each of the samples finer than the 150 μm (No. 100) sieve was ground to pass the 45 μm (No. 325) sieve; the resulting powders were then X-rayed as tightly-packed powders in a barium hydroxide-saturated nitrogen atmosphere to prevent carbonation of the cement paste.

9. All X-ray patterns were made with an X-ray diffractometer using nickel-filtered copper radiation.

10. Small portions of each powdered sample were placed in dilute hydrochloric acid (HCl) to see whether soluble effervescent carbonates were present.

Results and discussion

11. Apparently intact concrete. The composition of the blended material from each end of each of the four cores is similar. Except for the presence of a small amount of gypsum, this composition is a normal one for the crystalline components of concrete. The presence of gypsum indicates in all probability that it formed as a reaction product between sulfuric acid and calcium hydroxide in the core near the tunnel. The composition is shown below by groups:

Hydrated Cement Constituents	Aggregate Constituents	Reaction Product with H_2SO_4
Ettringite	Quartz	Gypsum
Calcium hydroxide	Plagioclase and potassium feldspars	
	Calcite	
	Dolomite	
	Mica	
	Kaolinite clay	

A2

No residual unhydrated cement was detected by X-ray diffraction in the concrete cores from Piedmont Lake. There appears to be a small amount of unhydrated calcium aluminoferrite, a cement constituent, in the concrete cores from Clendening Lake.

12. Soft, deteriorated concrete. Both samples are similar; they are composed of gypsum and quartz and a trace of mica.

13. It is apparent that the original cement constituents have been replaced by gypsum in the soft, deteriorated concrete and that this conversion is most pronounced in concrete above the waterline in the tunnels. The change from intact to deteriorated concrete does not suggest the mechanism of sulfate attack for two reasons. First, the reaction product should be ettringite rather than gypsum if it were sulfate attack. Secondly, the reaction would probably be widespread rather than localized if it were sulfate attack.

14. The change does indicate some form of acid attack since the acid soluble carbonates in the aggregate (calcite, dolomite) are missing in the deteriorated concrete. This was definitely shown by placing small amounts of these samples in dilute hydrochloric acid. Attack by acid water is not indicated since the deterioration is above the waterline. The pH of the water from both tunnels is 7.1 which also shows that the water is not acid. Therefore, the mode of occurrence and the composition of the reaction product suggest that the deterioration resulted from attack by sulfuric acid. Presumably the original step was the action of anaerobic bacteria below the waterline forming H_2S gas in the tunnels. The emergence of the gas at the water surface and its subsequent alteration to sulfuric acid by autotropic bacteria makes the attack possible. The presence of about 500 and 300 ppm of sulfates in the tunnel water at Clendening and Piedmont Lakes, respectively, shows that there is an original supply of sulfur to make this a feasible reaction.

15. The report by ACI Committee 515[2] provides general guidance on materials to use to protect concrete against various kinds of chemical attack. Specific comments about possible remedial action to stop this deterioration will be discussed in the overall report.

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Log of Two Horizontal 4-Inch-Diameter Concrete Cores from Outlet Tunnel,
Clendening Lake, Huntington District

Depth, ft

Core C-1 (HUN-8 CON-1(A))
Near upstream end of tunnel.
Outer surface has aggregate
particles in relief. This
suggests removal of about
1/4 in. of original surface.

Formed surface;
end of core

Core C-2 (HUN-8 CON-1(B))
Near midpoint of tunnel.
Aggregate in relief on
outer surface suggests
removal of about 1/8 in.
of original surface.

Broken surface on end
of core

General Comment
Both cores are intact concrete.
They contain a natural sand and
gravel of mixed composition.
Maximum aggregate size is about
1 in. The core ends show that
tunnel surfaces are iron stained.

Vertical scale: 0.1 in. = 0.1 ft

Figure A1.

Log of Two Horizontal 4-Inch-Diameter Concrete Cores from Outlet Tunnel,
Piedmont Lake, Huntington District

Depth, ft
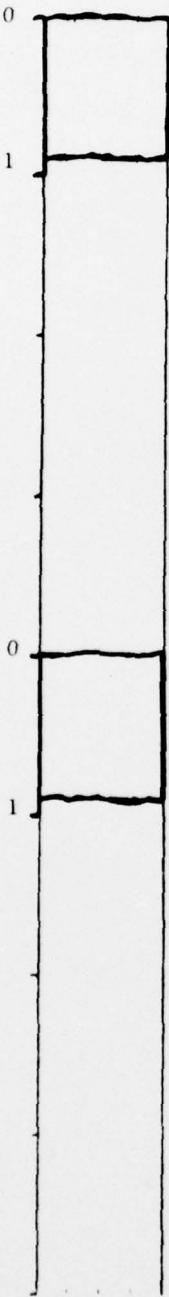
Core P-1 (HUN-8 CON-2(A))
Near upstream end of tunnel.
Exposed aggregate on surface
suggests that about 1/8 in.
of original surface is gone.

0

1

End is partially a formed
and partially a broken
surface

Core P-2 (HUN-8 CON-2(B))
Near midpoint of tunnel.
Surface has tarry black
coating.

0

1

End is formed surface
with tarry black coating
on it.

General Comment
Both cores are intact concrete.
They contain natural sand and
gravel of mixed composition.
The maximum aggregate size is
about 1-1/2 in.

Vertical scale: 0.1 in. = 0.1 ft

Figure A2.